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Title page

A new method for the performance of external chest compressions during hypogravity simulation.

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Abstract

Introduction: 2015 UK resuscitation guidelines aim for 50-60mm depth when giving external chest compressions (ECCs). This is achievable in hypogravity if the rescuer flexes and extends their arms during CPR, or using a new method trialed; the 'Mackaill-Russomano' (MR CPR) method.

Methods: 10 participants performed 3 sets of 30 ECCs in accordance with 2015 guidelines. A control was used at 1Gz, with eight further conditions using Mars and Moon simulations, with and without braces in the terrestrial position and using the MR CPR method. The MR CPR method involved straddling the mannequin, using its legs for stabilization. A body suspension device, with counterweights, simulated hypogravity environments. ECC depth, rate, angle of arm flexion and heart rate (HR) were measured.

Results: Participants completed all conditions, and ECC rate was achieved throughout. Mean (\pm SD) ECC depth using the MR CPR method at 0.38Gz was 54.1 \pm 0.55mm with braces; 50.5 \pm 1.7mm without. ECCs were below 50mm at 0.17Gz using the MR CPR method (47.5 \pm 1.47mm with braces; 47.4 \pm 0.87mm without). In the terrestrial position, ECCs were more effective without braces (49.4 \pm 0.26mm at 0.38Gz; 43.9 \pm 0.87mm at 0.17Gz) than with braces (48.5 \pm 0.28mm at 0.38Gz; 42.4 \pm 0.3mm at 0.17Gz). Flexion increased from approximately 2° - 8° with and without braces respectively. HR did not change significantly from control.

Discussion: 2015 guidelines were achieved using the MR CPR method at 0.38Gz, with no significant difference with and without braces. Participants were closer to achieving the required ECC depth in the terrestrial position without braces. ECC depth was not achieved at 0.17Gz, due to a greater reduction in effective body weight.

Keywords:

Cardiopulmonary resuscitation; Basic life support; External chest compressions; Hypogravity simulation

Introduction

Cardiopulmonary resuscitation (CPR) is a method used in cardiac arrest situations to maintain perfusion to vital organs, with an aim of achieving the return of spontaneous circulation (ROSC). It is a technique developed in the 1960s¹⁸ and has been refined many times, with evidence-based research ever since³. CPR is a skill that is taught to healthcare professionals as well as laypersons worldwide, and the guidelines regarding its delivery are updated every 5 years by international committees³⁰. CPR is critical to maintain a constant blood flow in these situations, to avoid ischemia of these organs and ultimately the death of the casualty. However, the quality of CPR delivered by the rescuer is a crucial factor in whether or not resuscitation is successful, and has several components²⁷.

The most recent guidelines published in 2015 by the UK Resuscitation Council state that four main criteria contribute to the successful delivery of CPR³⁰. These criteria refer to the depth of external chest compressions (ECCs)³⁵, the rate at which these ECCs are performed¹², how much the chest recoils after each ECC²⁴ and the degree to which the CPR is uninterrupted throughout²⁵. Delivering CPR which meets these four criteria is essential in order to achieve the ROSC, perfuse vital organs and successfully resuscitate the subject.

Traditionally, 'out of hospital' CPR is delivered with the rescuer kneeling by the side of the subject, as this allows ECCs to be delivered with movement between ECCs and ventilations with minimal interruptions. Evidence shows, particularly in 'out of hospital' cardiac arrests⁷, that continuous compressions are of greater benefit to minimize interruptions in the less trained^{14,36}. CPR performed by straddling the subject may be considered when two providers are available or when it is not possible to perform ECCs from the side. This can occur in confined spaces or on a stretcher, with the other provider giving ventilations overhead²⁷.

A study by Nasiri et al (2014) compared the kneeling, or terrestrial, position with the straddling position whilst giving bag valve mask ventilations to mannequins, and found that performing CPR in the straddling position led to increased ECC and ventilation rates with better quality of resuscitation overall, with regards to the guidelines at the time of the study²³. A review by Davey (2014) also found that in simulated conditions, CPR performed in the straddling position resulted in CPR quality similar to that kneeling by the side of the subject¹⁴. This evidence suggested

that a single rescuer may prefer to perform CPR in the straddling position if performing CPR alone, particularly if they are using a bag valve mask.

Another study by Lei et al (2010) evaluated the efficacy of ECCs delivered using the straddle position and also found this method of CPR to be as effective as the terrestrial position, with rescuers kneeling by the side²¹. From this, we can assume that in certain situations CPR can be performed in the straddling position, with no detrimental effect on the quality of CPR delivered to the subject.

In the terrestrial setting, the evidence from the 2015 UK resuscitation council guidelines show that effective, quality CPR can be delivered to patients at 1Gz³⁰. CPR in a simulated hypogravity environment has demonstrated difficulty in achieving the 2015 guidelines for adequate depth and rate of ECCs^{1,7}. A study by Baers et al (2016) found that a reduction in weight due to the simulated hypogravity conditions limited free acceleration of the rescuer's chest, and therefore the amount of force that could be generated, which affected the rescuer's ability to reach the required depth as set out by the 2015 guidelines¹. This reduction in weight and limited free acceleration can make ECCs more fatiguing, which will rapidly affect the depth, rate and potentially the quality of ECCs in hypogravity environments, where the rescuer's overall body weight will be reduced. The reduction in quality of ECCs will reduce organ perfusion and decrease the chance of achieving a ROSC²².

Previous studies have shown, using the older guidelines, that in hypogravity there is a natural flexion of the upper limbs to compensate for this effective reduction in body weight and aid in the generation of force⁷. These studies have shown arm flexion angles up to 16 degrees compared to 1 - 2 degrees in terrestrial CPR at 1Gz⁷. Other studies into hypogravity CPR have also found this^{28,32}. They suggest that flexing the arms is a countermeasure needed due to the reduced ability to accelerate the chest and is a way to overcome these difficulties. These studies also suggest that the weight of the rescuer may be a predictor of depth for simulated hypogravity environments¹.

However, this adaptation does not address the problem of stability when performing ECCs in the terrestrial position in simulated hypogravity environments. Anecdotally, rescuers in hypogravity simulation felt their knees and legs lifting off the ground with each chest compression, which can interfere with the delivery of effective CPR.

Baers et al (2016) also suggested that some rescuers may require an alternative CPR technique to overcome their lower bodyweight and muscle mass to ensure that they can perform adequate ECCs in accordance with the current CPR Guidelines¹.

To address these issues, a new method called the 'Mackaill-Russomano' (MR CPR) method was developed to be used in a hypogravity environment or its simulations. This method is similar to the terrestrial straddling position²¹, with the aim of stabilizing the rescuer whilst delivering ECCs by tucking their heels and lower legs underneath the subject's legs.

The landscape of space flight is currently in a state of change. There is an increase in private companies investing in sub-orbital flights and plans for longer duration missions by space agencies. To date, no astronaut has suffered a cardiac arrest requiring CPR, but there have been several minor cardiac events that have self resolved^{31,14}.

There is a possible increased cardiovascular risk in greater microgravity exposure, due to its known deconditioning effects^{2,34}, and less strict screening criteria in laypersons being exposed to microgravity with these cultural changes. Both of these could possibly lead to an increased incidence of cardiovascular events in microgravity or space flight¹⁵. Despite the remote possibility of a serious cardiac event in these scenarios, it is still possible and needs to be prepared for. The prospect of Exploration Class Missions, increased mission duration, and other inherent risks and stresses of space flight, make the likelihood of a serious cardiac event a real risk that needs robust evidence-based protocols.

The aim of this study was to determine the efficacy of the MR CPR method in delivering CPR in simulated hypogravity, both in simulated Moon and Mars gravitational environments, to see if this method was able to achieve the 2015 UK Resuscitation Council guidelines³⁰. As well as this, the study aimed to compare the efficacy of the MR CPR method to terrestrial CPR in 1Gz, simulated Moon and Mars environments, using braces to restrict arm flexion and without them to determine if this influenced the quality of the CPR delivered.

Methods

Participants

Ten healthy volunteers participated in this study (Table I). The study was conducted at the Microgravity Centre, Pontifícia Universidade do Rio Grande do Sul (PUCRS), Brazil, where the protocol was approved by the PUCRS Ethics and Research Committees. The participants provided a signed a consent form prior to the beginning of the study.

Age	24.5 ± 2.8
Height (m)	1.75 ± 0.08
BMI (kg/m²)	24.2 ± 2.4
Weight (kg)	
- Terrestrial (+1Gz)	74.2 ± 11.1
- Mars (+0.38Gz)	39.5 ± 5.6
- Moon (+0.17Gz)	30.1 ± 4.2

Table I. Demographic data of participants in this study (mean ± SD); n=10

Equipment

A standard CPR mannequin (Resusci Anne Skill Reporter, Laerdal Medical Ltd., Orpington, UK) was modified to include a linear displacement transducer capable of measuring ECC depth and rate. Real-time feedback of each ECC was provided via a modified electronic guiding system with a light-emitting diode (LED) display to represent the 2015 guidelines in terms of rate and depth. The LED display consisted of a series of colored lights that indicated depth of ECCs (red, 0 - 39 mm; yellow, 40 - 49 mm; green, 50 - 60mm). An ECC rate of 100 compressions/min⁻¹ was set using an electronic metronome. A 6 second interval between each ECC set represented the time taken for two mouth-to-mouth ventilations.

A custom-built body suspension device (BSD) was used to simulate hypogravity gravitational fields for the participants. The BSD was developed by the Microgravity Centre, PUCRS, and has been used in several other microgravity and hypogravity studies successfully^{1,7}. It is pyramidal in shape and the frame is made of carbon steel bars of 6 cm x 3 cm thickness (base area measures, 300 cm x 226 cm; height, 200 cm). A study by Baers et al (2016) shows a schematic diagram illustrating the BSD¹.

In order to simulate hypogravity, there is a counterweight system made of 20 bars of 5 kg each, which is attached to the participant via a pulley system and body harness. The body harness was attached via the use of the steel cross bar and a nylon rope with carabiners fastened at each end. A safety carabiner was also attached to the participant's back. For simulated Mars (0.38Gz) and Moon (0.17Gz) gravitational fields, which were used in this study, the correct counterweights were applied. The necessary counterweights were calculated using the following equations:

$$RM = (0.6BM \times SGF)/1G \quad \text{Equation 1}$$

$$CW = 0.6BM - RM \quad \text{Equation 2}$$

RM is the relative mass in kilograms (kg), 0.6BM is the percentage of upper body mass, SGF is the simulated gravitational force (m.s⁻²), 1Gz = 9.81 m.s⁻² and CW is the counterweight in kg.

During the performance of ECCs, the mannequin was placed supine on the floor with

the participant adopting either the terrestrial kneeling CPR position or the MR CPR method, as described in the introduction. In order to perform the MR CPR method, the rescuer straddled the mannequin, the same way as they would during terrestrial CPR in the straddle position²¹. The rescuer then tucked their heels and lower legs underneath the mannequin's legs, using the weight of each of the mannequin's legs to stabilize them. This then enabled the rescuer to stay stationary whilst performing ECCs. Depending on which gravitational environment was being used, the weight of the mannequin's legs in that gravitational field would be calculated and added to the mannequin's legs in order to place over the rescuer's legs when performing CPR. The weight of the legs was calculated as follows, assuming the mannequin was an average weight of 80kg:

$$RM = 0.4BM \times SGF/2 \quad \text{Equation 3}$$

40% of the body mass of an individual will be the legs, so we use the same equation as above then divide by 2. Based on that, it was calculated that it equated to 6kg on each leg for Mars simulation and almost 3kg in each leg for Moon simulation that needed to be added to the mannequin's legs. The weight was equally distributed across the legs and strapped to the mannequin's legs.

Angle of elbow flexion was measured using a custom-built electrogoniometer on the participant's dominant arm (developed by the Microgravity Centre, PUCRS). The electrogoniometer consisted of two aluminum bars (200.0 mm x 20.0 mm x 3.0 mm) covered with rubber material and was fastened over the participant's lateral epicondyle via a series of straps; this allowed the change in flexion to extension (from 0° - 90°) to be accurately measured. The electrogoniometer was calibrated for 0 - 90° prior to the beginning of each condition. The device was connected with a linear 10 kΩ potentiometer and powered by a 5-V power source^{28,32}.

Arm braces were attached to the participants during the relevant 'braces' conditions (Table II) in order to restrict the ability to move the elbow joint. This was done using a semi-cylindrical shaped brace strapped to the extensor surface of the lower arms covering from the wrist to the elbow, which prevented flexion of the arms.

An Onyx 9500 fingertip pulse oximeter (Nonin Medical Inc., Plymouth, MN, USA) measured the participant's heart rate (HR) throughout each condition.

Procedure

Each participant was required to carry out a total of 9 conditions during this study (Table II). The first condition for every participant was the control, performing terrestrial CPR at 1Gz. They then performed CPR in simulated hypogravity, which included using the terrestrial CPR method with and without arm braces (in order to prevent and allow elbow flexion respectively), and the MR CPR method with and without braces. They performed these 4 conditions in both Mars (0.38Gz) and Moon (0.17Gz) simulated gravitational environments.

Condition

1Gz Terrestrial CPR

Moon (0.17Gz):

- Terrestrial CPR (braces on)
- MR CPR method (braces on)
- Terrestrial CPR (braces off)
- MR CPR method (braces off)

Mars (0.38Gz):

- Terrestrial CPR (braces on)
 - MR CPR method (braces on)
 - Terrestrial CPR (braces off)
 - MR CPR method (braces off)
-

Table II. List of the 9 conditions performed by the participants.

The participants' height in meters and weight in kg were measured before beginning the experiment, and body mass index (BMI, kg.m^{-2}) was calculated from these. The participants' weight in both Martian and Moon environments was calculated from this so that the relevant counterweight could be applied; using Equations 1 and 2. After signing a consent form, participants were first familiarized with the equipment, as well as both the terrestrial CPR and MR CPR method. Participants were required to

demonstrate that they were able to perform both methods effectively in terms of technique.

For each condition, each participant performed three sets of 30 ECCs with a 6 second interval between, to simulate two rescue ventilations, in accordance with 2015 adult CPR guidelines, at a ratio of 30:2 (compressions: breaths)³⁰. This 6 second gap was displayed with a visual countdown display as described previously, as well as feedback from the researchers. The study employed a within- participant repeated measures design, with each participant being their own control. After the control position was performed at 1Gz, the order of simulated hypogravity conditions and four methods were randomized using a random computer generator.

Participants rested for 5 minutes prior to performing CPR to record baseline values of their heart rates. Each participant then performed three sets of 30 ECCs with a 6 second interval between these sets, as described above. All participants began performing ECCs with the terrestrial CPR method at 1Gz, and the 8 following conditions were randomized as mentioned to give a total of 9 conditions performed by each participant. Between each set of ECCs, participants were given time to rest until their heart rates returned to their baseline value.

ECC rate and depth, as well as angle of elbow flexion, were measured throughout the study. A DataQ acquisition device, with 10 bits of measurement accuracy, rates up to 14,400 samples.s⁻¹ and USB interface, was used (DATAQ Instruments Inc., Akron, OH, USA). The device supported a full-scale range of ± 10 V and a resolution of ± 19.5 mV. WinDag data acquisition software allowed for the conversion of volts to the necessary units used (mm for depth; degrees for elbow flexion). Two input channels were used during data collection: one from the chest system of the mannequin and the other from the elbow electrogoniometer. The mannequin's chest system was calibrated between participants using inputs of 0 and 60 mm to account for the 2015 CPR guidelines. The elbow electrogoniometer was calibrated for the full range prior to each protocol; full extension of the arm (0°) and 90° of elbow flexion. HR was recorded before and immediately after the last set of ECCs was completed in each condition.

Statistical analysis

Depth and change in elbow flexion angle were recorded with DataQ acquisition software of each individual ECC. From these electronic traces, the ECC depth, rate and elbow flexion were calculated and were reported as mean values (\pm SD). Elbow flexion was calculated as a range from the minimum to maximum angle of an individual ECC. The ECC depth was analyzed in two different ways: maximum depth (DMax) achieved and true depth (DT), which was calculated using the equation, with Dlirecoil representing the depth of inadequate recoil^{1,32}.

$$DT = DMax - Dlirecoil$$

HR was recorded at baseline, prior to each ECC and immediately afterwards. The HR was compared as a percentage change from baseline. The measurements mentioned above were derived post hoc from the DataQ acquisition software, and used GraphPad Prism v7.03 for analysis. Statistical comparisons were performed on physiological variables (HR) using a one-way ANOVA test. With regards to the ECCs and elbow flexion data, a two-way ANOVA was used to compare results between the 9 conditions. The two independent variables compared in the two-way ANOVA tests were the position of delivering ECCs and the presence of braces to restrict arm flexion. A 95% confidence interval (CI) calculation around the mean was used. The level of significance was set prior to the study as $p \leq 0.05$.

Results

All 10 participants completed the nine sets of ECCs. The mean (\pm SD) true depth (DT) of all three sets of ECCs at 1Gz, Lunar and Martian simulated gravitational environments for the 2015 guidelines are displayed in Figures 1 and 2, respectively. The mean (\pm SD) DT was within the 2015 guidelines in 1Gz using the control position (56.6 ± 2.0 mm), and in 0.38Gz using the MR CPR method with (54.06 ± 2.6 mm) and without braces (50.5 ± 3.2 mm). The mean (\pm SD) DT fell just short of the required depth in the terrestrial position in 0.38Gz without (49.4 ± 3.4 mm) and with braces (48.5 ± 3.1 mm). The mean (\pm SD) DT did not meet the required depth in any of the conditions in 0.17Gz, but was closer using the MR CPR method with (47.5 ± 3.1 mm) and without braces (47.4 ± 3.5 mm), than using the terrestrial position without (44.0 ± 3.5 mm) and with braces (42.4 ± 3.3 mm).

In both simulated Martian and Lunar hypogravity, the MR CPR method was able to achieve a significantly greater DT compared to the terrestrial position when braces were used (Lunar $p=0.0066$; Martian $p=0.0009$). This significant improvement was not seen when braces were off and the rescuers arms were allowed to flex.

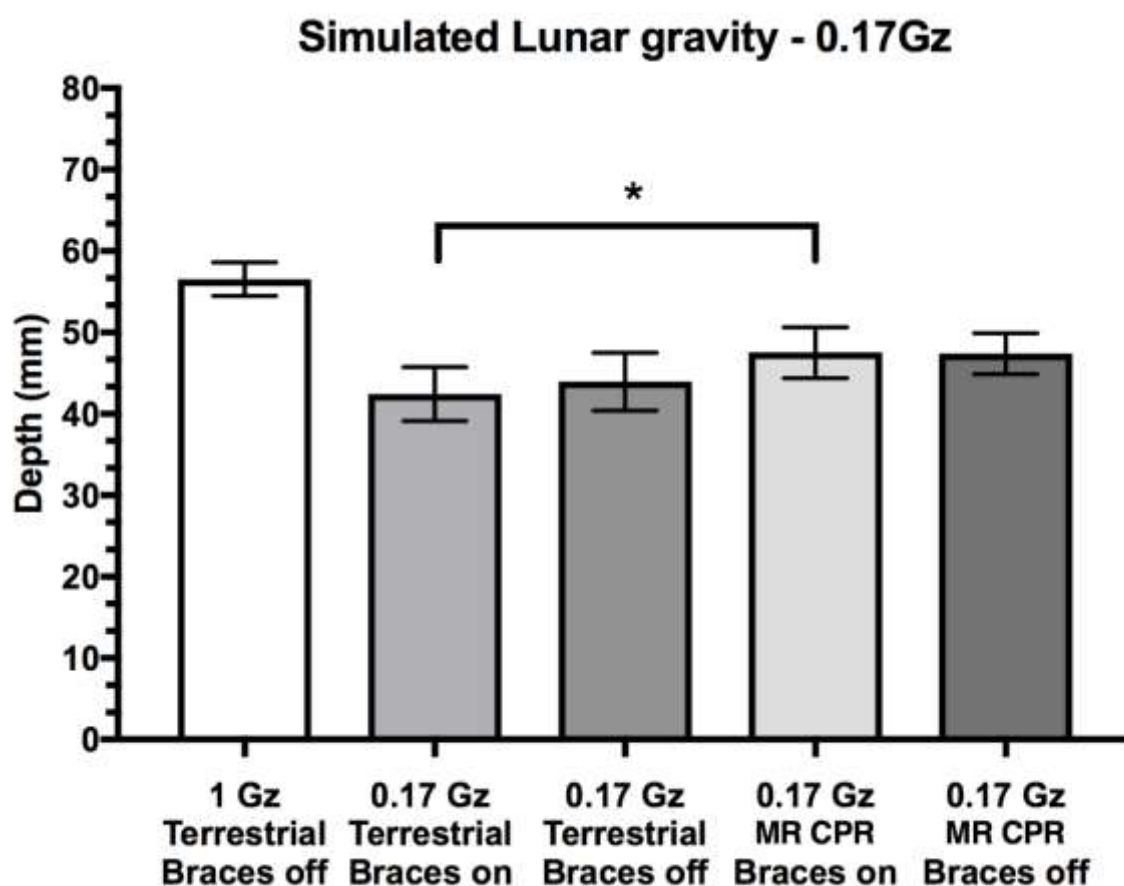


Figure 1. Comparison of ECC true depth (DT) in simulated lunar gravity.

* denotes a significant difference between the terrestrial and MR CPR method when braces are on, $p < 0.05$. Error bars represent 1 standard deviation from the mean.

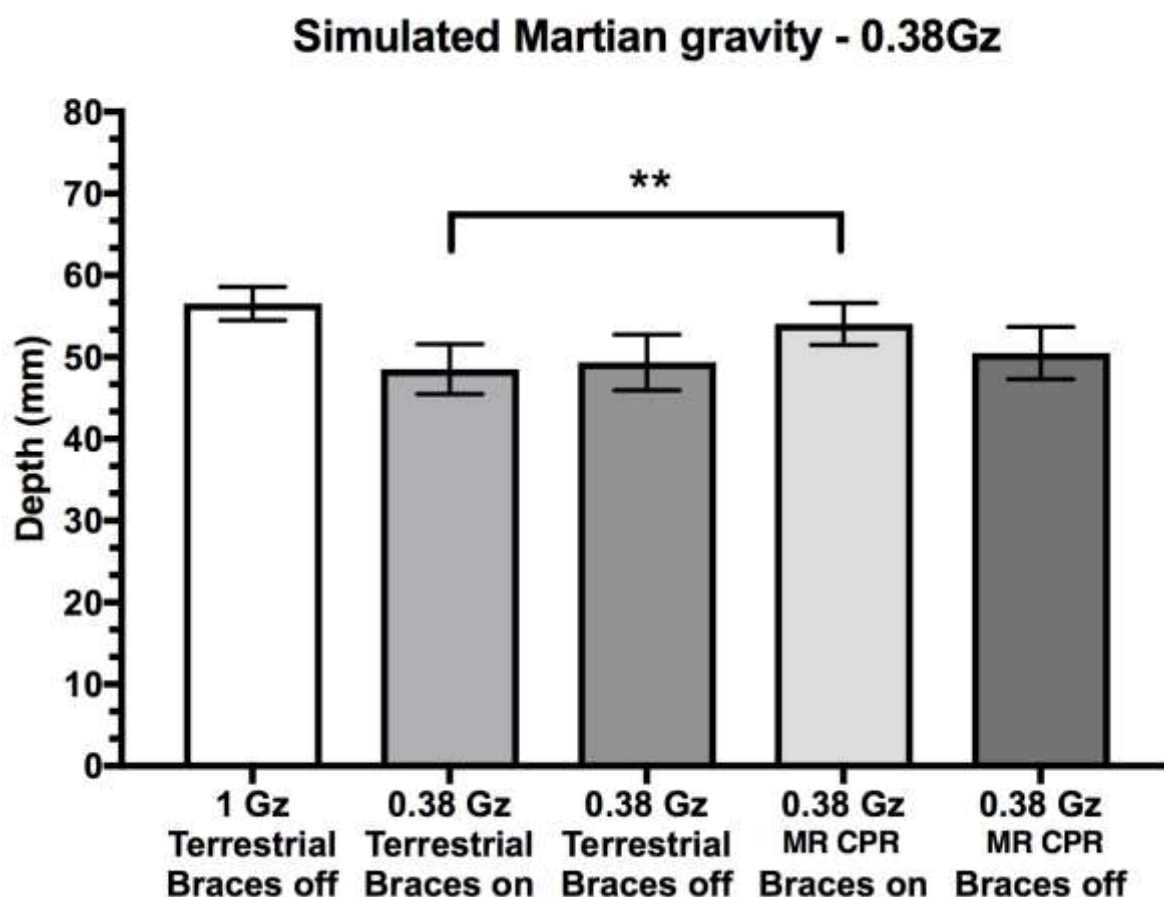


Figure 2. Comparison of ECC true depth (DT) in simulated Martian gravity.

* denotes a significant difference between the terrestrial and MR CPR method when braces are on, $p < 0.01$. Error bars represent 1 standard deviation from the mean.

In the control position at 1Gz, there was a decline in performance of mean (\pm SD) ECC depth between the first set ($58.7 \pm 2.2\text{mm}$) and the last set ($54.9 \pm 1.7\text{mm}$) of ECCs. This trend was seen in all positions in both gravitational simulations, with a decrease in depth achieved from the first ECC set to the last. In simulated 0.38Gz, mean (\pm SD) ECC depth was maintained above 2015 guideline standards across all sets. A two-way ANOVA test revealed that there was a statistically significant interaction between the number of ECC sets performed and DT, $F(2,81) = 6.37$, $p = 0.0027$. A Tukey post hoc test revealed that a significant decrease in achieved depth was only seen in the control setting of 1Gz ($p = 0.0073$). However, when using the MR CPR method, ECCs were closer to the required depth when participants wore braces than when they did not.

The mean (\pm SD) ECC rate was successfully maintained between 100 – 120 compressions/min⁻¹ for each set within each gravitational condition, which is in keeping with 2015 guidelines³⁰ (Table III). In each position, ECC rate was higher when the participant did not wear braces compared to when they did. In the terrestrial position in 0.38Gz and 0.17Gz, ECCs were also of a higher depth when the subject did not wear braces (49.4mm and 44.0mm, respectively) than when they did (48.5mm and 42.4mm, respectively).

Gravitational Condition	Position	Braces	ECC Depth (mm)	ECC Rate (compressions/min ⁻¹)
1Gz	Terrestrial	No	56.6 +/- 2.0	101.7
0.38Gz	Terrestrial	Yes	48.5 +/- 3.1	104.6
	Terrestrial	No	49.4 +/- 3.4	106.4
	MR CPR method	Yes	54.1 +/- 2.6	105.6
	MR CPR method	No	50.5 +/- 3.2	107.5
0.17Gz	Terrestrial	Yes	42.4 +/- 3.3	104.7
	Terrestrial	No	44.0 +/- 3.5	106.4
	MR CPR method	Yes	47.5 +/- 3.1	105.6
	MR CPR method	No	47.4 +/- 3.5	107.5

Table III. Mean (+/- SD) true depth (DT) and mean rate of ECC sets

Figure 3 illustrates the degree of elbow flexion in the nine different ECC settings. The mean (\pm SD) range of elbow flexion of the participant's dominant arm in 1Gz using the control position was 3.8 ± 1.5 degrees. In 0.38Gz simulated gravity, the mean (\pm SD) range of elbow flexion of the participant's dominant arm using the MR CPR method was 1.6 ± 0.42 degrees with braces, and 7.2 ± 2.1 degrees without braces. The mean (\pm SD) range of elbow flexion of the participant's dominant arm in the terrestrial position was 1.8 ± 0.84 degrees with braces and 6.5 ± 1.6 degrees without. In 0.17Gz simulated gravity, the mean (\pm SD) range of elbow flexion of the participant's dominant arm using the MR CPR method was 2.4 ± 1.4 degrees with braces and 8.1 ± 2.6 degrees without. The mean (\pm SD) range of elbow flexion of the subject's dominant arm in the terrestrial position was 2.0 ± 0.59 degrees with braces and 8.6 ± 3.1 degrees without. Without the use of braces, elbow flexion significantly increased in Lunar and Martian conditions when compared with the control environment at 1 Gz ($p < 0.05$). The use of the MR CPR method or terrestrial position did not significantly influence the degree of elbow flexion.

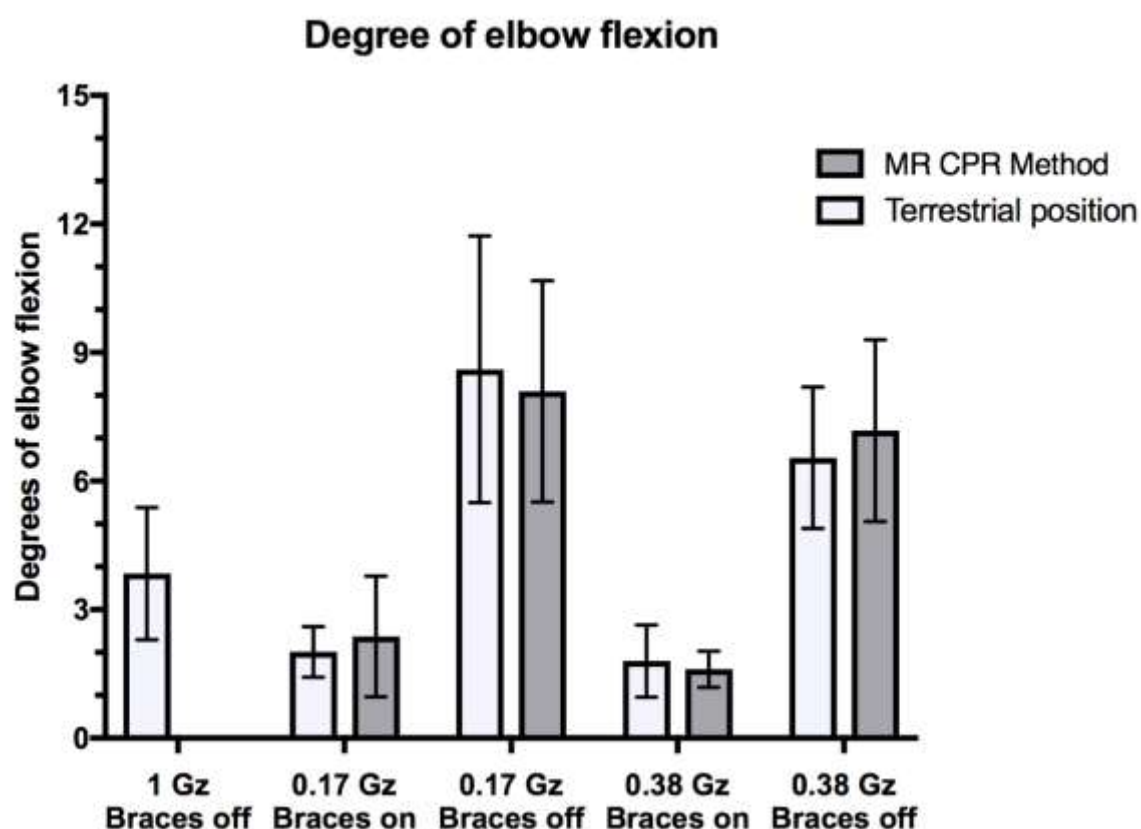


Figure 3. The change in arm flexion angle at 0.38 Gz and 0.17 Gz. Error bars represent 1 standard deviation from the mean.

Elbow flexion significantly increased in simulated hypogravity CPR without braces ($p < 0.001$). A two-way ANOVA test showed there was no significant relationship between the terrestrial position, MR CPR method and elbow flexion, $F(3,72) = 0.40$, $p = 0.75$. The mean (\pm SD) rescuer HR at baseline, post-ECCs, as well as percentage change in all three gravitational conditions and each position is illustrated in Table IV. The mean (\pm SD) participant HR at baseline was 78.2 ± 13.4 , with the greatest increase in HR seen in the MR CPR position at 0.38Gz using the MR CPR method with no braces. The smallest increase in HR was with the MR CPR method in 0.38Gz with braces. Even though HR significantly increased from baseline in all nine ECC settings, no significant relationship between the two positions and HR was seen.

Condition	Position	Braces	HR post-ECCs (\pm SD)	Increase from baseline (%)
Baseline			78.2 (± 13.4)	
1Gz	Terrestrial	N/A	130 (± 11.4)	69
0.38Gz	Terrestrial	Yes	126 (± 8.5)	63
	Terrestrial	No	127 (± 13.9)	65
	MR CPR method	Yes	117 (± 13.4)	53
	MR CPR method	No	131 (± 11.9)	71
0.17Gz	Terrestrial	Yes	124 (± 17.0)	60
	Terrestrial	No	130 (± 20.3)	68
	MR CPR method	Yes	125 (± 15.1)	62
	MR CPR method	No	129 (± 15.2)	67

Table IV. Summary of changes in mean (\pm SD) HR from baseline as percentage increase.

Discussion

Astronauts and future space tourists will be exposed to microgravity for some part of their journey when travelling the ISS, the Moon or Mars in the future. Studies into CPR in microgravity are well established with three methods currently accepted.^{13, 29} This study, however, explores the difference in methods that may need to be applied when reaching the surface of the Moon or Mars, as the method will need to be altered to suit that particular gravitational environment.

There have been several studies comparing CPR methods in a microgravity environment, both in parabolic flight and other Earth based simulations^{13, 29}. Jay et al (2003), along with other groups, have studied several microgravity CPR methods in parabolic flight, including Handstand, side, waist straddle, Evetts-Russomano (ER) and Reverse Bear Hug methods^{13, 11}. Researches also evaluated extraterrestrial CPR methods using the BSD, showing the Handstand method to provide the best depth of compression and be the least fatiguing²⁹. Due to different gravitational fields, however, not all of these methods are applicable to hypogravity, so making a direct comparison is difficult. However, this is the first paper to compare and contrast different methods in hypogravity simulation.

With the growing interest in space tourism and highly anticipated manned missions to Mars in the future, there needs to be an effective Basic Life Support (BLS) protocol in place before sending astronauts to another planet with a lower gravitational environment. This is the first study to evaluate the novel MR CPR method. In addition to this, it looked to investigate the difference between performing ECCs in hypogravity simulation with immobile and mobile arms, using 2015 guidelines, looking at the physiological impact of each position on the rescuer when delivering ECCs.

ECC rate was maintained throughout all conditions performed in this study, in keeping with 2015 guidelines³⁰. It was noted that ECC rate was higher when the participants did not wear braces compared to when they did. This is likely due to the possibility that the participants were forced to keep their arms straight and solely rely on accelerating their upper body weight in order to generate enough force for each ECC. When assessing the true depth (DT) of ECCs, it is apparent that overall

participants found it easier to reach the required depth as per the 2015 guidelines³⁰ in the control position at 1Gz than in 0.38Gz and 0.17Gz simulated environments. This confirms what previous studies have shown, by effectively reducing a participant's or rescuer's weight, performing CPR becomes harder and more strenuous¹. Adequate depth of ECCs was achieved in the 0.38Gz gravity simulated environment when performing CPR using the MR CPR method, both when participants wore braces and when they did not. However, the required ECC depth was not achieved when participants used the terrestrial position in 0.38Gz, both with and without the participants wearing braces, but participants were closer to achieving the required depth in the terrestrial position when they did not wear braces than when they did. A previous study by Russomano et al (2013) found that ECCs above 50mm were achievable using the terrestrial CPR position in hypogravity, particularly at 0.38Gz³². This study, however, consisted only of male participants and they suggested that higher muscle mass in males was a contributing factor to this³².

In the 0.17Gz conditions, the required depth as per the 2015 guidelines was not achieved in either position. However, overall participants were closer to achieving the required guidelines when using the MR CPR method with braces and without braces. As with the 0.38Gz simulated environment, when participants performed CPR using the terrestrial position in 0.17Gz, participants were closer to achieving the required depth when they did not wear braces than when they did. Evidence from the 2015 guidelines shows that ECC depths of 50 - 60mm are associated with better outcomes for patients³³. However, there is an argument to be made that with no other evidence to support another more effective method, that compressions at the depths seen by using the MR CPR method could be of some clinical benefit in these isolated hypogravity environments.

In 1Gz using the terrestrial position, there was an average decrease in depth (\pm SD) of 3.8mm (\pm 5.5) from the first ECC set to the third, which could be due to fatigue. This trend of a decrease in depth between the first and last ECC set was seen in all conditions. The trend was only slight in the terrestrial position in 0.38Gz with a decrease in depth of 0.17mm (\pm 5.6) with braces and 0.33mm (\pm 3.1) without braces between the first and last ECC set. However, there was a larger decrease between the first and last ECC set when using the terrestrial position in 0.17Gz, with a

decrease in depth of 0.6mm (± 3.2) with braces and 1.7mm (± 3.9) without braces. This indicates that it is more tiring to perform and maintain effective ECCs in hypogravity environments; this is most likely due to the effect of reduced body weight and therefore acceleration and force generation. This confirms findings from previous studies in hypogravity^{7,28}; implying that weight is potentially a pivotal factor in force generation using these CPR methods in hypogravity.³²

The position with the lowest increase in HR from baseline, excluding the control condition using terrestrial CPR, was using the MR CPR method without braces in 0.38Gz simulation, which consequently showed the highest depth achieved. The most fatiguing positions in terms of increases of HR from baseline were the positions in which braces were not worn, both in 0.38Gz and 0.17Gz gravitational simulation, despite achieving greater depths of ECCs. The reason for this is most likely that more effort is required when flexing the arms to achieve depth in hypogravity.

The mean range of elbow flexion of the participant's dominant arm was more when participants did not use braces in each condition, which is expected as their range of movement is restricted. Overall there was a higher degree of elbow flexion in 0.17Gz compared to terrestrial CPR and 0.38 Gz, and this is most likely due to the lower simulated gravitational field and the need for increased flexion to generate sufficient force to deliver adequate ECCs. This confirms what previous studies have identified, that with a reduction in weight the participant has a reduced ability to generate force by accelerating their chest and needs to use their upper limb musculature to compensate²⁸.

When restricted with the braces, participants are unable to flex their arms as much as without braces, hence unable to generate sufficient force and making CPR more difficult. The increased arm flexion angle seen in hypogravity builds on previous evidence that in hypogravity the traditional straight arm terrestrial method needs to be modified to allow for arm flexion so ECCs can meet the 2015 guidelines. Future protocols need to reflect this change in CPR method and consider the implications for terrestrial CPR in certain populations, such as lighter healthcare professionals to allow for more effective CPR by flexing the arms to generate force.

It is difficult to directly transfer experimental data from this study to a Lunar or Martian environment. but our data suggests that the MR CPR method is superior in delivering effective CPR than the terrestrial method in a hypogravity environment. To assess the efficacy of CPR in hypogravity, we employed a simulation in the study design. This study used a BSD to simulate hypogravity, which allowed the choice of gravitational field simulation, in this case Lunar and Martian. Limitations of this and other hypogravity ground simulations are well documented in previous studies^{28,32}.

Possibly the most common form of microgravity and hypogravity simulation used is parabolic flight. Parabolic flight would be a superior alternative to the BSD in some respects when studying CPR in hypogravity, as it would provide a high fidelity hypogravity environment. These hypogravity parabolic flights would more accurately represent acute cardiopulmonary system changes in the rescuer and perhaps influence their CPR performance by fully unloading the body, compared to the BSD where the limbs and head are not unloaded. However, all simulations have strengths and weaknesses²⁰. The main weakness of parabolic flights is the relatively short duration of hypogravity that they offer, between 25 seconds for 0.17Gz (Moon) and 32 seconds for 0.38Gz (Mars)^{20, 26}. These bursts of hypogravity do not allow for continuous sets of ECCs to be performed and for certain physiological measurements to be made, such as fatigue or performance of ECCs over time. This is the advantage of using a BSD over parabolic flights, as it allows the study of several gravitational fields over a prolonged period of time.

There are several physiological changes which take place in microgravity and hypogravity environments which cannot be reproduced during simulation on Earth or during a parabolic flight⁹. Simulations cannot take into account the long-term physiological changes which might affect both the rescuer and subject, such as muscular deconditioning and the resulting decrease in muscle strength⁹. Subjects would be exposed to a microgravity environment for several months on their journey to Mars, encountering multi-system deconditioning and potential radiation exposure, before their body would have to re-adapt to a hypogravity environment on arrival⁹.

This study simulated the patient with a Resusci Anne mannequin, used internationally for training and research purposes, to measure the rate, depth and

chest recoil in participants performing CPR. It is well known that one of the physiological changes in prolonged microgravity is the displacement of the rib cage in the cranial direction at end expiration, resulting in a more circular shape^{4,10}. Mannequins used in research studies cannot recreate this chest shape or the effects on the cardiopulmonary system, but we can hypothesize that with an increased distance between the rib cage and the heart, deeper chest compressions may be required, which supports the use of MR CPR method further. However, there is limited evidence of what will happen to the chest displacement when returning to a gravitational field, such as when arriving on Mars after 6 months of microgravity exposure. One could argue that the changes are transient, like with current ISS astronauts on returning to Earth after 6 months aboard the ISS, and that when astronauts land on Mars, the displacement of the chest will return to its normal position.

Another limitation of these mannequins, and of this study, is a lack of more in-depth monitoring, such as end tidal carbon dioxide (PetCO₂) and blood flow. In reality, a decrease in any of these parameters would have clinical consequences on the subject, such as hypoperfusion of the organs, leading to end organ damage, such as hypoxic brain injury²². This reinforces the importance of finding a suitable method which meets the Resuscitation Council's guidance with regards to rate, depth and chest recoil, with the potential to provide optimal CPR in hypogravity conditions³⁰. There have been a limited number of studies that have been able to do provide this level of evidence. Johnston et al (2004) used a swine model to measure PetCO₂ during CPR in a parabolic flight, showing the effectiveness of several microgravity CPR methods¹⁶. Future work in this area should consider this level of monitoring to assess the effectiveness of these hypogravity methods, including the MR CPR method.

A hypothetical scenario to consider is performing ECCs while conducting an Extravehicular Activity (EVA) in a modified Extravehicular Mobility Unit (EMU) for the surface of Mars or the Moon. There are many logistics to consider, such as providing ventilations whilst in an EMU and the stiffness of the crew members suit when attempting to compress the chest. For example, will it allow for 50-60mm of compression? Putting the latter to one side, the terrestrial guidelines highlight that

ECCs are crucial for effective CPR and in the case of out-of-hospital cardiac arrests, laypersons should favor continuous chest compressions over providing ventilations to minimize interruptions to ECCs²⁵. There are a lot of obstacles to overcome in order for crew members to be able to perform ECCs in a hypogravity environment, including significant deconditioning due to prolonged microgravity exposure⁹. However, these protocols need to be established so they can be followed effectively in emergency situations.

In addition to crew members performing ECCs, crews living in the isolated environment of space, Moon and Mars need to consider the use of mechanical devices as part of a BLS protocol. Mechanical devices, such as LUCAS and Autopulse, are being used more commonly in both in and out-of-hospital cardiac arrest situations in a terrestrial setting⁵. It is well known that fatigue can affect the quality of chest compressions. If you consider this as well as the muscular deconditioning seen in microgravity, these devices could be beneficial in providing optimal CPR over a prolonged period of time in isolated settings of microgravity and hypogravity. A study by Jay et al (2003) found that use of a mechanical device could potentially provide a great advantage when performing CPR in space¹³. However, as on earth, we cannot rely wholly on these devices and a BLS protocol should be in place in case of mechanical dysfunction, time constraints and in situations where a mechanical device is not available. There is also a cost and weight constraint involved in taking these devices into space, as well as the task of calibrating the device which is time consuming. Time is a pivotal factor in the case of a cardiac arrest, and chest compressions should be started in any instance without delay while other crew members retrieve the mechanical device.

Another potential significant issue for the performance of restrained CPR or use of mechanical CPR devices is vibration of the spacecraft. Vibration could be an issue if the patient is restrained to the floor of the space station or spacecraft, possibly affecting the structure if vibration becomes too great. However, there are no studies on this subject yet, and future work is needed in these areas to form complete CPR guidelines. Future work can be done with mechanical devices in ground-based microgravity and hypogravity simulation, BSD as well as parabolic flight, before

applying their use in space. Although their design may need to be adapted to the requirements of the space craft being used.

Gender, weight and muscle mass is another important issue when considering CPR in reduced gravitational fields. A study by Baers et al (2016) compared the efficacy of ECCs between males and females in hypogravity simulation, with their results showing that weight was a strong predictor of true depth achieved¹. This study also showed that both males and females can perform ECCs in Martian gravity, but females had significantly lower depth of ECCs in Lunar gravity¹. These studies used a side straddle method, and our data shows that the MR CPR method is superior to this, as our study, on average across all subjects, achieved the required depth of chest compressions. However, future work needs to evaluate specific gender differences as well as weight and muscle mass, and its effects on CPR performance.

Weight is not a factor in microgravity CPR, as crewmembers cannot utilize their weight to perform ECCs, but muscle mass has been suggested to be¹⁷. This was suggested in a study done by Kordi et al (2012) that concluded that both genders can perform effective ECCs during simulated hypogravity, however woman do not perform ECCs as effectively in microgravity conditions, particularly using the ER method¹⁷. Again, future work is needed in this area to fully evaluate factors that affect females performing CPR in microgravity in order to develop countermeasures.

This study evaluated a new method of CPR for a hypogravity environment. Results suggest that with the added stability given to the participant and rescuer, using the MR CPR method helped achieve the criteria necessary for effective ECCs in 0.38Gz gravity conditions. Using the 2015 CPR guidelines, neither the terrestrial nor MR CPR method were able to achieve the required ECC depth at 0.17Gz. However, the MR CPR method was marginally better and may still provide a clinical benefit during a cardiac arrest in a lunar environment. The results also showed that when performing ECCs, they are more effective when performed without braces, allowing an increased range of elbow flexion to generate force for ECCs. Despite these findings, there are areas of future research that are needed to validate the MR CPR method as well as add to the body of evidence to develop a comprehensive basic and advanced life support protocol for extraterrestrial environments.

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